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Developing a Platoon-Wide Eco-Cooperative Adaptive Cruise Control (CACC) System

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Abstract — **Connected and automated vehicle (CAV) technology has become increasingly popular. As an example, Cooperative Adaptive Cruise Control (CACC) systems are of high interest, allowing CAVs to communicate and cooperate with each other to form platoons, where one vehicle follows another with a predefined spacing or time gap. Although numerous studies have been conducted on CACC systems, very few have examined the protocols from the perspective of environmental sustainability, not to mention from a platoon-wide consideration. In this study, we propose a vehicle-to-vehicle (V2V) communication based Eco-CACC system, aiming to minimize the platoon-wide energy consumption and pollutant emissions at different stages of the CACC operation. A full spectrum of environmentally-friendly CACC maneuvers are explored and the associated protocols are developed, including sequence determination, gap closing and opening, platoon cruising with gap regulation, and platoon joining and splitting. Simulation studies of different scenarios are conducted using MATLAB/Simulink. Compared to an existing CACC system, the proposed one can achieve additional 2% energy savings and additional 17% pollutant emissions reductions during the platoon joining scenario.**

Index Terms* — *Eco-Cooperative Adaptive Cruise Control (Eco-CACC), Energy consumption, Pollutant emissions

I. INTRODUCTION

Nowadays, many cities in the U.S. are challenged with serious traffic congestion issues, due to continued travel demand growth, a higher number of motor vehicles, and lower gasoline prices. Admittedly, for the past few years, cities that have experienced more economic improvement are at a higher risk to face worsening traffic conditions, resulting in increased pollutant emissions and decreased travel efficiency. In terms of average time wasted on the road, Los Angeles for example was ranked the first among all the U.S. cities for its notorious traffic congestion, where on average 81 hours were wasted per commuter during the year of 2015 [1]. It was also estimated by [2] that there were 3.1 billion gallons of energy wasted worldwide due to traffic congestion in 2014, which equated to approximately 19 gallons per commuter.

Significant efforts have been made by researchers and policy makers around the world to address these transportation issues. One of the promising solutions is the connected and automated vehicle (CAV) technology that has inspired various innovative intelligent transportation applications. For example, the Eco-Approach/Departure (Eco A/D) application uses signal phase and timing (SPaT) information sent from a roadside equipment via wireless communications to connected vehicles to encourage “green” approaches to signalized intersections, which can provide up to 13% energy reduction benefits for a coordinated corridor above baseline [3]. The Cooperative Adaptive Cruise Control (CACC) system is considered to be another effective solution to increasing the traffic flow efficiency by taking advantage of the vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) communications. By sharing information among vehicles, a CACC system allows vehicles to form platoons and be driven at harmonized speed with smaller constant time gaps between vehicles. It improves the roadway capacity and stabilizes the traffic flow by reducing vehicle-following gaps and uncertainties in driver behavior, without compromising the safety or expanding the roadway infrastructure.

Since the first prototype CACC system was developed, a significant amount of effort has been put into the assessment and enhancement of system performance, by either simulation or field operational test, in terms of stability, communicability, safety, mobility, and driving comfort. However, relatively little research has focused on the development and evaluation of the so-called Eco-Cooperative Adaptive Cruise Control (Eco-CACC) system, which considers energy-efficient strategies/maneuvers in the CACC protocols.

As a subsequent study of the USDOT’s AERIS (Applications for the Environment: Real-time Information Synthesis) program, we propose a V2V-based Eco-CACC system which aims to reduce the platoon-wide energy consumption and pollutant emissions at different stages of the CACC operation, including platoon formation, platoon in-operation, and platoon dissolution.

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In terms of the paper layout, Section II introduces some background information of the proposed platoon-wide Eco-CACC system. Section III details the algorithm and protocol for each stage of the Eco-CACC operation. Section IV conducts preliminary evaluation of the system and results are shown. Section V provides further discussion and outlines some future steps.

II. BACKGROUND

A. The State of the Art of CACC Systems

During the last decade, significant development in the CACC systems has been achieved, where a variety of research and field implementation has been conducted around the world. Jia [4] *et al.* reviewed the related work of platoon-based vehicular cyber-physical systems, and discussed the fundamental issues such as vehicle platooning/clustering, CACC, platoon-based vehicular communications, etc. The design, development, implementation, and testing of a CACC system was presented by [5], where two controllers were included which managed the gap-closing maneuver to the leading/preceding vehicle and the gap-regulation strategy once the vehicle joins the platoon. Shladover *et al.* [6] described the definition and classification of the CACC system to help clarify the distinctions among different types of automatic vehicle following control strategies. A distinction was also made between V2V-based CACC systems and I2V-based CACC systems, and it turned out that in V2V-based CACC systems, communication provides enhanced information so that vehicles could follow their predecessors with higher accuracy, faster response, and shorter gaps, resulting in enhanced traffic flow stability and possibly improved safety. V2V communication methodology is also adopted by our Eco-CACC system in this study. B. van Arem *et al.* [7] used the traffic-flow simulation model MIXIC to study the impact of CACC on traffic-flow characteristics, demonstrating an improvement of traffic-flow stability and a slight increase in traffic-flow efficiency by equipping vehicles in highway-merging scenario with CACC.

Recently, Wang *et al.* [8] proposed a novel CACC system based on the distributed consensus theory, where distributed consensus algorithm and protocol were designed for platoon formation, merging maneuvers, and splitting maneuvers. Only local cooperation of connected vehicles were required to form this system, hence the communication complexity was largely reduced. The core of this CACC system is the double-integrator distributed consensus algorithm

$$\begin{aligned}\ddot{x}_i(t) &\\ = -\Big[x_i(t) - x_j\left(t-\tau_{ij}(t)\right) &+ c_j + \dot{x}_j\left(t-\tau_{ij}(t)\right) t_{ij}^g b_i\Big] \\ -\gamma\left[\dot{x}_i(t) - \dot{x}_j\left(t-\tau_{ij}(t)\right)\right]& \\ i = 2, \dots, n, j = i-1 & \qquad (1)\end{aligned}$$

where the acceleration of vehicle i at time t is based on the absolute position difference and the velocity difference between itself with its preceding vehicle j. This algorithm takes the length c_j and braking ability b_i of different vehicles into account. Communication delay $\tau_{ij}(t)$ is also included in the algorithm, making the system more realistic and applicable. A simulation study was conducted in MATLAB/Simulink, showing the system enables connected vehicles to form platoon, to restore from disturbances, and to process merging and splitting maneuvers. Sensitivity analysis on the CACC system was also carried out, concluding a value of 7.5 for the damping term γ is both safe and comfortable for the human passengers in the certain parameters setting.

B. The Energy Perspective of CACC Systems

Another primary motivation of developing the CACC system is to reduce energy consumption and pollutant emissions. Researchers have been investigating the main factors of high energy consumption levels and pollutant emissions generated by vehicles. Barth *et al.* [9] found that CO_2 emissions could be reduced by up to almost 20% through three different strategies: congestion mitigation strategies that allow traffic to flow at better speeds, speed management techniques that reduce excessively high free-flow speeds to more moderate conditions, and shock wave suppression techniques that eliminate the acceleration and deceleration events associated with the stop-and-go traffic. The CACC system allows vehicles to be driven in platoons with the same moderate speed and much shortened time gap (thus increasing the throughput), therefore the aforementioned three strategies are all realized to some extent. In addition, since all vehicles but the leading one in the CACC system follow their proceeding vehicles with a much shorter vehicle-following gap, the presence of the boundary layer along the platoon reduces air resistance, hence energy consumption is further decreased [10].

C. The MOVES Model

In this study, the U.S. Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES) is adopted to perform the multiple scale analysis on the environmental impacts of the proposed Eco-CACC system. The MOVES model can estimate tailpipe emissions from mobile sources covering a wide range of pollutants such as carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) [11]. In the modeling procedure, a variety of information is required as the system inputs, including vehicle type, driving cycle, acceleration/deceleration, and road grade. The model performs a series of calculations based on some predefined look-up tables which have been carefully developed to precisely characterize vehicle operating process (OpMode), and then provides estimates of platoon-wide energy consumption and pollutant emissions.

III. PLATOON-WIDE ECO-CACC PROTOCOL

In this section, we propose a platoon-wide Eco-CACC system, developing different protocols for different stages of the CACC operation along freeway, i.e., platoon formation, platoon in-operation, and platoon dissolution. The key protocols for the involved vehicle(s) at each stage may include sequence determination, gap closing and opening, platoon cruising with gap regulation, and platoon joining and splitting. Under each protocol, we assume all vehicles are CACC-enabled. For simplicity in description and development, we further assume in this study that all vehicles are identical in characteristics such as vehicle type, vehicle length, acceleration/braking ability.

A. Sequence Determination

Before a free-agent vehicle (say, vehicle i) tries to join a platoon from the back, a fundamental issue is to determine which place this new vehicle should fit in the platoon. A heuristic protocol is the so-called "entry-time" based sequencing, where the order of each vehicle in the platoon depends on the time when it joins. The sooner the vehicle joins the platoon, the closer it is to the leading position. More specifically, when vehicle i arrives in the communication range of the platoon, it sends a "joining" request to the platoon. Once the request is confirmed, vehicle i will (changing lanes if necessary) approach the end of platoon and become the last vehicle of the new platoon. Any new comer will attach to the platoon behind it. In such a manner, the joining of new free-agent vehicles will not affect the other vehicles already in the platoon. However, when a vehicle or multiple vehicles are leaving from the platoon for destination, disturbance will be generated that affect the followers.

Another heuristic sequencing protocol is based on the distance to destination when the free-agent vehicle is joining the platoon. The longer the vehicle's distance to destination is, the closer it is to the leading position in the platoon. For example, as vehicle i arrives in the communication range of the platoon, it sends both the "joining" request and its destination information to the platoon. Then the platoon decides if this newcomer should be accommodated and where it would fit. If vehicle i's destination is further than vehicle j in the platoon but closer than vehicle $j-1$, then vehicle i will become the jth vehicle after joining the platoon and vehicle j will become vehicle $j+1$. Under this protocol, disturbances may be presented to some vehicles in the platoon when new free-agent vehicles join, but the operation for those leaving vehicles become much more efficient and less irritating to others since they are always the last. In the context of mandatory (e.g., exit the freeway) and discretionary lane-change (e.g., joining the platoon) [12], this protocol should cause less disturbance to the platoon than the entry-time based one; therefore, it is adopted in this study.

It is admitted that a more comprehensive sequence determination protocol may be developed in order to achieve higher platoon-wide energy efficiency, which can be one of the topics for future study.

B. Gap Closing and Opening

Generally speaking, there are two complementary protocols for a platoon to accommodate the weaving in and out maneuvers of a free-agent vehicle: gap closing and gap opening. The gap closing process happens when a following vehicle tries to catch up with its preceding vehicle from a certain distance. The following vehicle should first accelerate to gain a large speed difference with its preceding one, then cruise at this rather high speed for a while to shorten the gap, and finally decelerate to the same speed as its preceding one.

In this study, we propose a piecewise trigonometric function family to model the relationship between relative speed and relative distance of two consecutive vehicles to achieve higher energy efficiency for gap closing. It is noted that the similar idea has been proposed by the authors and extensively validated in the Eco-Approach and Departure (EAD) application at signalized intersections [13]. Given the relative speed and relative distance at time $t=0$ (without loss of generality), we can determine the planned trajectory for the gap closing controller by solving the following optimization problem:

$$\min \Delta V_{h0} \tag{2}$$

subjects to

$$\Delta V(t) = \begin{cases} \frac{1}{2}(\Delta V_{h0}+\Delta V_0)-\frac{1}{2}(\Delta V_{h0}-\Delta V_0)\cdot\cos(m\cdot t)\,, t\in\left[0,\frac{\pi}{m}\right) \\ \Delta V_{h0}, t\in\left[\frac{\pi}{m},t_1\right) \\ \frac{1}{2}\Delta V_{h0}+\frac{1}{2}\Delta V_{h0}\cdot\cos[n\cdot(t-t_1)]\,, t\in\left[t_1,t_1+\frac{\pi}{n}\right) \end{cases} \tag{3}$$

$$\frac{\pi}{2m}(\Delta V_{h0}+\Delta V_0)+\Delta V_{h0}\left(t_1-\frac{\pi}{m}\right)+\frac{\pi}{2n}\Delta V_{h0}=\Delta D_0 \tag{4}$$

$$\Delta V_0 \le \Delta V_{h0} \le \Delta V_{max,0} \text{ and } t_1+\frac{\pi}{n}\le t_{th} \tag{5}$$

$$0\le\frac{m}{2}(\Delta V_{h0}-\Delta V_0)\le a_{max} \text{ and } 0\le\frac{n}{2}\Delta V_{h0}\le|a_{min}| \tag{6}$$

$$\frac{m^2}{2}(\Delta V_{h0}-\Delta V_0)\le Jerk_{max} \text{ and } \frac{n^2}{2}\Delta V_{h0}\le Jerk_{max} \tag{7}$$

where ΔD_0 is the difference between the initial gap and the desired gap of two consecutive vehicles; ΔV is the speed difference between two consecutive vehicles; ΔV_0 is the initial speed difference; ΔV_{h0} is the optimal speed difference peak calculated at time $t=0$; $\Delta V_{max,0}$ is the largest speed difference (at time $t=0$) constrained by the speed limit posted on the roadway; m and n are the angular frequencies of trigonometric functions, respectively; t_{th} is the time threshold to complete the gap closing maneuver; a_{max}, a_{min} are the maximum and minimum acceleration, respectively; and $Jerk_{max}$ represents the maximum jerk (i.e., change rate of acceleration in time) to address driving comfort issue. In this study, we choose $a_{max}=2.5\ \text{m/s}^2$, $a_{min}=-2.5\ \text{m/s}^2$, and $Jerk_{max}=10\ \text{m/s}^3$ [14]. Fig. 1 illustrates an example of the proposed trajectory. As can be seen from the figure, after time $t=t_1+\frac{\pi}{n}$, two consecutive vehicles should travel at the same speed, while maintaining a desired gap.

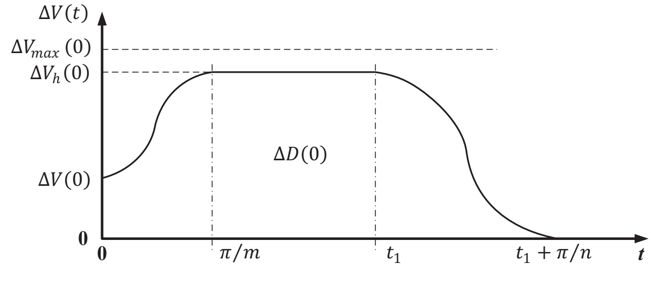

Fig. 1. Trajectory planning for gap closing.

The gap opening process happens when a following vehicle tries to create a larger gap with its preceding vehicle to allow other vehicles to join the platoon. Similar to the energy-efficient trajectory designed for gap closing, another optimization problem can be formulated with the constraints of another piecewise trigonometric function (see Fig. 2) to model relative speed versus relative distance of two consecutive vehicles for gap opening.

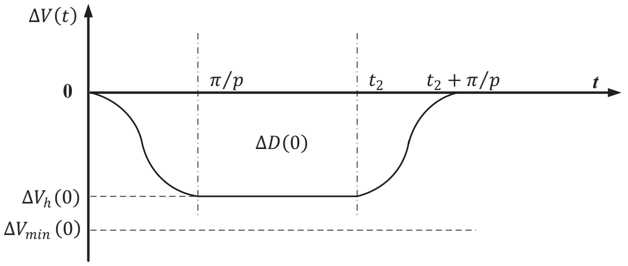

Fig. 2. Trajectory planning for gap opening.

C. Platoon Cruising with Gap Regulation

The cruising speed of a platoon is critical, since the optimal value leads to the minimization of energy consumption and pollutant emissions. Based on the authors' previous research [9], the estimated CO_2 emissions factor (in gram/mile) for light-duty vehicles on a flat road can be fitted as a convex function of cruising speed (e.g., the solid line in Fig. 3), i.e., a fourth-order polynomial that can be expressed by

$$\ln(y) = b_0 + b_1 \cdot x + b_2 \cdot x^2 + b_3 \cdot x^3 + b_4 \cdot x^4 \quad (8)$$

where y is the CO_2 emissions in g/mi ,and x is the cruising speed in mph. The coefficients for each fitted curve are given in TABLE I. In this study, we choose the eco-cruising speed as 45 mph.

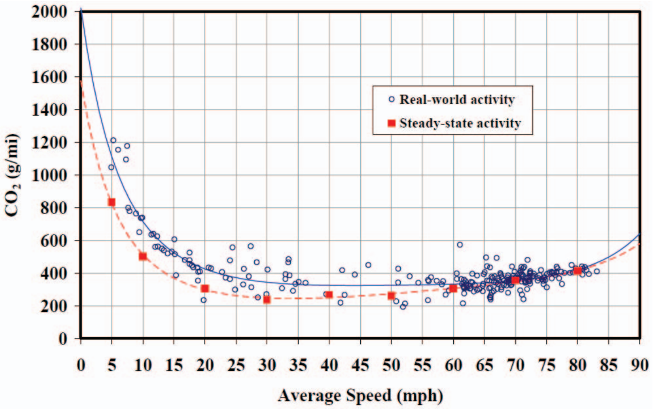

Fig. 3. CO_2 emissions as a function of average speed.

TABLE I. DERIVED LINE-FIT PARAMETERS

Parameters	Real-World	Steady-State
b_0	7.613534994965560	7.362867270508520
b_1	- 0.138565467462594	- 0.149814315838651
b_2	0.003915102063854	0.004214810510200
b_3	- 0.000049451361017	- 0.000049253951464
b_4	0.000000238630156	0.000000217166574

On the other hand, to guarantee the string stability [15], we design a gap regulation controller by following the recommendation in [5], which can be stated as

$$X_i(s) = \frac{D(s)+G(s)K_P(s)}{1+G(s)[K_P(s)P_P(s)+K_L(s)P_L(s)]} X_{i-1}(s) \quad (9)$$

where $X_i(s)$ and $X_{i-1}(s)$ are the positions of two consecutive vehicles; $D(s)$ is the communication delay; $G(s)$ is the vehicle model; $K_P(s) = 0.45s + 0.25$ is the preceding gap error controller; $K_L(s) = 0.15s + 0.1$ is the leading gap error controller; $P_P(s)$ and $P_L(s)$ are preceding car-following policy and leading car-following policy, respectively, and can be defined as

$$P_P(s) = h_P(s) + 1 \quad (10)$$

$$P_L(s) = h_L(s) + 1 \quad (11)$$

with $h_P(s)$ and $h_L(s)$ being the time-gap target values with respect to the preceding and leading vehicles, respectively.

D. Platoon Joining and Splitting

The protocols in Section III*B* and III*C* address the maneuvers of vehicles that are in the platoon, while platoon joining and splitting protocol is aimed at the maneuvers of vehicles that try to join or split from the platoon. According to [16], there are generally four different cases for the lane change within the platoon maneuvers: 1) free-agent-to-free-agent lane change; 2) free-agent-to-platoon lane change; 3) platoon-to-free-agent lane change; and 4) platoon-to-platoon lane change. This protocol focuses on the second and third cases.

For the case where vehicle i (as a free agent) tries to join a platoon on the adjacent lane, after the sequence is determined (e.g. as the jth vehicle of the platoon), a "ghost" vehicle (i.e., the red rectangle in the left-most sub-plot of Fig. 4 with respect to vehicle $j-1$ in the platoon will be created on the same lane as vehicle i. This "ghost" vehicle has all the same parameters but the lateral position as vehicle $j-1$. Then, vehicle i will close the gap with the "ghost" vehicle using the proposed gap closing protocol. After that, vehicle i will send a merging signal to vehicle $j+1$ in the platoon. Upon receiving the merging signal, another "ghost" vehicle (i.e., the green rectangle in the middle sub-plot of Fig. 4) with respect to vehicle i will be created in front of vehicle $j+1$, and vehicle $j+1$ starts to open a gap for vehicle i based on the proposed gap opening protocol. After the gap is fully created, vehicle $j+1$ sends a confirmation signal to vehicle i, and vehicle i joins the platoon.

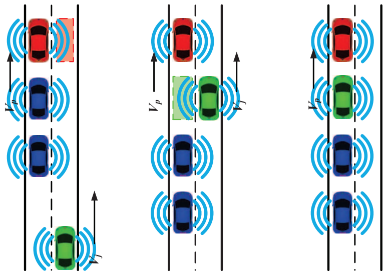

Fig. 4. A vehicle joins an existing 3-vehicle platoon from adjacent lane.

The case where vehicle j (in the platoon) tries to split from the platoon is much simpler. It has been studied in [6] that there are two strategies for splitting maneuvers, or so called CACC string dissolution. The most efficient action for the departing driver is to make a lane change towards the off-ramp without any deceleration. Another strategy for the departing driver could be to firstly deactivate the CACC function by tapping on the brakes before changing lanes, creating a split in the CACC string, and becoming the manually driver leader of the platoon until the vehicle moves out of the original lane. Since we adopt the destination-based sequencing protocol (see Section III*A*), the driver can simply take over the lateral control of the vehicle and perform the lane change without adjusting the velocity longitudinally, once the splitting mode is activated. After vehicle j completes the lane change, a confirmation signal will be sent to vehicle $j+1$ which will change its preceding vehicle index from j to $j-1$, and therefore closes the gap. A new platoon is formed, where vehicle $j+1$ becomes vehicle j, and vehicle $j+2$ becomes vehicle $j+1$, and so on.

IV. PRELIMINARY EVALUATION AND RESULTS

MATLAB/Simulink [17] is used to conduct numerical simulation of the proposed Eco-CACC system under two different scenarios. All vehicles in our system are assumed to be connected vehicles with the ability to send and receive information among them. Results of platoon-wide energy consumption and pollutant emissions are illustrated in different scenarios, and are also compared with the distributed consensus-based CACC system proposed in [8].

A. Platoon Formation

In this part, a platoon formation scenario is analyzed where two vehicles on the same lane form a platoon by the proposed gap closing algorithm. The parameters of this scenario are listed in TABLE II.

TABLE II. VEHICLE PARAMETERS OF PLATOON FORMATION SCENARIO

Parameters	Value
Number of Vehicles	2
Length of Vehicles	16.4 feet
Length of Simulation Segment	1 mile
Initial Speed of Vehicles	45 mph
Final Speed of Vehicles	45 mph
Initial Inter-Vehicle Time Gap	7.58 s
Final Inter-Vehicle Time Gap	0.9 s

More specifically, the proceeding vehicle always cruise at 45 mph. The following vehicle has an initial speed of 45 mph and a final target speed of 45 mph as well, but it may conduct potential acceleration and deceleration processes to close the $(7.58 - 0.9 =)$ 6.68 s inter-vehicle time gap difference. After the MOVES model has been adopted to perform the multiple scale analysis on the environmental impacts of the proposed Eco-CACC system together with the existing distributed consensus-based CACC system, the platoon-wide benefits of our system are demonstrated in TABLE III.

As can be seen from TABLE III, for the platoon formation scenario, the proposed system has an improvement of 1.45 % on energy consumption over the distributed consensus-based CACC system. In addition, our system can also reduce the emissions of HC, $\mathrm{NO_x}$, and $\mathrm{CO_2}$, except for CO.

TABLE III. COMPARISON OF PLATOON-WIDE ENERGY CONSUMPTION AND POLLUTANT EMISSIONS ON PLATOON FORMATION

	HC (g)	**CO (g)**	**$\mathrm{NO_x}$ (g)**	**$\mathrm{CO_2}$ (g)**	**Energy (kJ)**
Consensus-CACC	0.146	4.68	0.758	684.2	9514.3
Eco-CACC	0.142	4.78	0.747	674.3	9376.6
Improved %	2.74	-2.14	1.45	1.45	1.45

B. Platoon Joining

To get better understanding of the system performance, a platoon joining scenario is simulated where a free-agent vehicle tries to merge in a three-vehicle platoon. The parameters of this scenario are listed in TABLE IV.

TABLE IV. VEHICLE PARAMETERS OF PLATOON JOINING SCENARIO

Parameters	Value
Number of Vehicles	4
Position of Free-Agent Vehicle in Platoon after Joining	2
Length of Vehicles	16.4 feet
Length of Simulation Segment	1 mile
Initial Speed of Free-Agent Vehicle	65 mph
Initial Speed of Platoon Vehicles	45 mph
Final Speed of Platoon Vehicles	45 mph
Initial Inter-Vehicle Time Gap Between Free-Agent Vehicle and Platoon Leading Vehicle	2.7 s
Final Inter-Vehicle Time Gap Between Free-Agent Vehicle and Platoon Leading Vehicle	0.9 s

Again, this scenario is simulated along a one-mile segment. We assume that based on the propose sequence determination protocol, the free-agent vehicle on the adjacent lane of the platoon has been decided to be the second vehicle in the platoon after the joining maneuver. The initial speed of the free-agent vehicle is $(65 - 45 =)$ 20 mph higher than the speed of the platoon. Initially, the free-agent vehicle has a 2.7 s inter-vehicle time gap with the leading vehicle of the platoon, while this decreases to 0.9 s after the free-agent vehicle joins the platoon. After adopting the MOVES model, the platoon-wide benefits of the proposed Eco-CACC system over the existing distributed consensus-based CACC system are demonstrated in TABLE V.

As can be seen from the results, our system has better performances on all the indices. For energy efficiency, the proposed Eco-CACC system has an improvement of 2.17 % over the distributed consensus-based CACC system. For pollutant emissions, our system can effectively reduce the emissions of HC, CO, NO_x, and CO_2 by 6.7%, 17.0%, 3.0% and 2.2%, respectively.

TABLE V. COMPARISON OF PLATOON-WIDE ENERGY CONSUMPTION AND POLLUTANT EMISSIONS ON PLATOON JOINING

	HC (g)	**CO (g)**	**NO_x (g)**	**CO_2 (g)**	**Energy (kJ)**
Consensus-CACC	0.312	10.14	1.425	1327.8	18462.7
Eco-CACC	0.291	8.42	1.382	1298.9	18061.6
Improved %	6.67	16.96	3.02	2.18	2.17

V. CONCLUSIONS AND FUTURE WORK

In this study, we have proposed a platoon-wide Eco-CACC system, which aims to minimize the overall energy consumption and pollutant emissions of a platoon during the CACC operation. A set of protocols have been developed for different stages, including sequence determination, gap closing and opening, platoon cruising with gap regulation, and platoon joining and splitting. Specifically, a gap-closing controller has been designed to determine the planned trajectory for the following vehicle to approach its preceding vehicle. Platoon joining and splitting protocols are developed for the scenarios where a free-agent vehicle tries to join a platoon, and where a vehicle in the platoon tries to leave the platoon. Simulation studies in MATLAB/Simulink have been conducted for two different scenarios: 1) platoon formation, and 2) platoon joining over a 1-mile segment. Compared to a existing CACC system, the proposed Eco-CACC system may reduce platoon-wide energy consumption by 1.45 % in platoon formation scenario, and by 2.17 % in platoon joining scenario, respectively.

It can be expected that many others issues may occur in the field implementation which have not been addressed in this study yet, such as road grade, different vehicle braking ability, communication delay, etc. This can lead to quite a few opportunities for future research. Moreover, this study focused on the system-level (cyber-space) of vehicles for Eco-CACC maneuvers, while actual vehicle dynamics model (physical-space) has been overlooked. The development of the cyber-physical Eco-CACC system can be another extension of this study.

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